Hydrographic conditions near the coast of northwestern Baja California: 1997 to 2004

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Abstract

The effects of the 1997-98 and 2002-04 El Niño on the upper waters in the continental shelf and slope regions off northwestern Baja California are explored with data from eight cruises taken in late spring from 1998 to 2004 and the summers of 1997 and 1998. Geostrophic velocities were calculated referenced to a specific volume anomaly surface separating the southward flowing California Current waters from the waters advected to the north by the California Undercurrent. The resulting fields show equatorward flow near the surface except in the summer of 1997, when a poleward jet was found in the upper 40 dbars. This shallow jet advected anomalously warm and salty waters characteristic of the 1997-98 El Niño, with its core found within 20-30 kms from the coast. By spring of 1998, the waters brought into the region by the jet had mixed across the pycnoline with the salty California Undercurrent waters below, resulting in high salinity levels on the density surfaces corresponding to the otherwise fresh California Current waters (25-26σ_t). By contrast, the 2002-04 El Niño stands out for the very fresh and cold waters found on the same density surfaces in late spring of 2003 and 2004, marking a pronounced presence of subarctic waters. The fresh conditions found on the latter years represent a nearshore expresion of the anomalous intrusion of subarctic waters observed 50-150 km from the coast of Southern California and Punta Eugenia, reported from July 2002 until April 2003. Our results suggest that the presence of this intrusion has continued to influence the region at least until May 2004.

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1 Introduction

The large scale surface circulation off northern Baja California is largely determined by the southern edge of the cyclonic Southern California Eddy, located in the Southern California Bight. The southern limit of this Eddy is found around 31-32°N, where the California Current turns eastwards (Reid et al., 1963; Wyllie, 1966; Lynn & Simpson, 1987), resulting in a biological and physical front known as the Ensenada Front (Pelaez & McGowan, 1986; Haury et al., 1993; Chereskin & Niiler, 1994; Espinosa-Carreon et al., 2004). Once the waters get about 200 km from shore, a branch of the California Current continues south-eastwards along the Baja California coast, the rest turning northwards to constitute the Inshore Current (or California Countercurrent), a shallow (< 200 m) poleward flow of relatively fresh waters found within 200 km of the Southern California coast (Wyllie, 1966; Chelton, 1982; Lynn & Simpson, 1987). At the subsurface, the poleward flowing California Undercurrent carries salty equatorial waters towards the north, its presence documented from southern Baja California to Alaska (Wooster & Jones, 1970; Chelton, 1982; Pierce et al., 2000; Strub & James, 2000). Its core off northern Baja California is found between 150-600 m, within 20 km of the continental slope

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(Wooster & Jones, 1970; Lynn & Simpson, 1987; Barton & Argote, 1980). The presence of a surface Inshore Current has not been documented off Baja California, although sustained poleward flows have been reported in the continental shelf off Tijuana (Alvarez et al., 1990), near 30°N (Barton et al., 1980) and at 31.3°N (Alvarez et al., 1984). Since northwesterly winds dominate in the region, coastal upwelling occurs year round off Baja California (Bakun & Nelson, 1977; Lynn, 1967; Huyer, 1983; Strub & James, 2000). As a result, salty California Undercurrent waters are brought close to the surface near the shore. The raise of the pycnocline towards the coast and corresponding upward sloping isopycnals suggest a southward surface flow, or a poleward subsurface flow decreasing in strength towards the surface. Congruous with this, various authors suggest the Inshore Current is a surfaced California Undercurrent (e.g. Lynn & Simpson, 1987; Badan-Dangon et al., 1989; Pares-Sierra & O'Brien, 1989).

Interannual variability in the California Current System and the thermohaline conditions off Baja California are closely linked to the El Niño Southern Oscillation. Warming of local waters constitute a typical effect of an El Niño event, which can result from either anomalous poleward advection of equatorial waters, onshore advection of offshore waters or a decrease in the local upwelling (e.g. Collins et al., 2002). The opposite conditions are more or less typical of La Niña events.

Most of what is now known on the thermohaline conditions and circulation off northern Baja California is the result from data collected regularly by the CalCOFI (California Cooperative Oceanic Fisheries Investigations) and IMECOCAL (Investigaciones Mexicanas de la Corriente de California) programs. The CalCOFI cruises visited the area regularly from 1949 to the mid 1980s, IMECOCAL continues to do so since 1997. The corresponding grid of hydrographic stations has the closest station to shore about 20-30 km from the coast; station spacings on each transect are about every 70 km, with distance between transects of 75 km. Hence, at the most two stations fall within the continental shelf and slope region. Relatively fewer studies have taken place near the coast (see review by Badan-Dangon et al. (1989), Pineda & López (2002), Tapia et al. (2004)), most of which collected direct measurements of the flow in the slope and shelf region. Only Barton & Argote (1980) collected hydrographic data within 40 km of the coast near 31°N, to study the effects of the winds on the thermohaline conditions during the peak of the upwelling season.

Along with biological sampling to assess vertical and horizontal distributions of larvae, hydrographic data were collected in the continental shelf and slope region in eight campaigns that took place between 1997 and 2004. The surveys started during the 1997-98 El Niño, continued through the 1999-02 La Niña, and finished sampling during the moderate El Niño that followed (Bograd et al., 2000; Durazo et al., 2001; Schwing et al., 2002; Venrick et al., 2003; McPhaden, 2004; Wolter, 2005). The 1997-98 El Niño was the strongest on record (McPhaden, 1999). The anomalous conditions observed off Southern California and Baja California in 1997 and 1998 seem to be the result of advection of salty and warm waters of southern origin, most likely to the south of Punta Eugenia (27.7°N, Lynn & Bograd (2002)). Durazo & Baumgartner (2002) proposed these were subtropical waters from the eastern Pacific that entered the region off Punta Eugenia. The period of the 2002-03 El Niño was particularly interesting given that its effects on the thermohaline conditions near the surface were overshadowed by an anomalous intrusion of fresh and cold Subarctic Water. As a result, record low salinities were reported from British Columbia to Baja California from July 2002 to April 2003, on the top 150 m and 100-200 km from the coast (Venrick et al., 2003; Huyer, 2003; Bograd & Lynn, 2003; Freeland et al., 2003; Durazo et al., 2005).

In this study we investigate the effects of the last two El Niño events on the hydrography and circulation on the continental slope and shelf region between Salsipuedes, Baja California, and La Jolla, California (Fig. 1). Special attention is given to the anomalous poleward surface jet found during the 1997-98 El Niño, which was previously reported offshore and to the north and south of the region studied (Durazo & Baumgartner, 2002; Lynn & Bograd, 2002). We also show that fresh and cold conditions prevail in the upper 100 m since May 2003, despite the positive El Niño phase. The latter result suggests that the effects of the 2002-03 Subartic water intrusion have been increasingly felt all the way into the coastal area off northern Baja California.

The data and methods used are presented in Section 2. The results are shown and discussed in Section 3, giving special attention to the geostrophic velocity fields, the effects of the 1997-98 El Niño, and the thermohaline conditions observed from 1999 to 2004. Section 4 offers a summary of the results.

2 Data and Methods

We use the Coastal Upwelling Index (CUI) calculated by the Pacific Fisheries Environmental Laboratory (PFEL) as a proxy to the wind conditions during the time of the hydrographic observations reported in this article. The CUI is the Ekman mass transport (per 100 m coastline) of surface water calculated from monthly pressure fields on a 3° mesh grid (Bakun, 1973; PFEL, 2005). We averaged the 30°N, 119°W and 33°N, 119°W monthly indices to obtain the approximate wind conditions for our region of study. Fig. 2 shows the resulting monthly CUI values from January 1997 until December 2005. Superimposed are the 58 year climatological monthly means, and the filled circles show the conditions corresponding to the time at which a hydrographic cruise took place. Positive CUI values denote offshore Ekman transport and hence upwelling favorable conditions.

The hydrographic stations collected during the Larvae in Alta and Baja California (LARBAJA) and Nearshore-Offshore Hydrodynamics and Population Ecology (NO-HYPE) cruises are shown in Fig. 1. The corresponding dates for each cruise are shown in Table 1. Distance between stations on each cross-shore section is 3-5 km. Ten cross-shore sections were carried out during the LARBAJA campaigns, each $\approx$ 7 km apart. During the NO-HYPE campaigns, five sections were sampled in the region with stations spacings of 3-5 km. Note that nine sections were sampled during the first NO-HYPE campaign. Each section is about 30-35 km long and has 7-8 stations. On each station, Conductivity-Temperature-Depth (CTD) profiles were taken from top to bottom except in the deeper regions, where casts were stopped between 1000-1500 dbar. Salinity profiles were derived from the conductivity measurements using the UNESCO 1983 polynomial (Fofonoff & Millard, 1983). For salinity calibration, water samples with Niskin bottles were collected for each cruise in a third of the stations at two depths, one near the surface and one at depth. The water samples were analyzed at the Ocean Data Facility at Scripps Institution of Oceanography using an Autosalinometer. For detailed description on the CTD data processing and calibration, see data reports (Pineda et al., 1997, 1998a,b, 1999; García-Córdova et al., 2004; Pérez-Brunius et al., 2004a,b,c).

We calculated potential density σ_t and spiciness π for each cast. Spiciness is a state variable most sensitive to isopycnal thermohaline variations and least correlated to the density field (Flament, 2002), and it has been widely used to study the characteristics and time evolution of the water masses associated with the California Current System (e.g. Chereskin & Niiler, 1994; Tisch et al., 1992; Durazo & Baumgartner, 2002; Lynn et al., 2003). Fresh and cold waters have low π, while salty and warm waters have high values. Fig. 3 shows a summary of the hydrographic data in a T/S-diagram with the different water masses found in the continental slope and shelf region, and isolines of π and σ_t. The average profile for each cruise was obtained from the mean temperature and salinity along isopycnals (Fig. 4), while the overall average profile was the average of the mean profiles of all the cruises (Fig. 3). This eliminates the bias towards cruises with a higher number of stations. Fig. 4 illustrates the changes in the water properties due to the strong El Niño of 1997-1998, the 1999-2002 La Niña that followed, and the weak El Niño conditions observed since then.

Geostrophic calculations for the California Current System are traditionally obtained using a reference level of 500 dbar. To be able to estimate the geostrophic flow in the shallow region of the continental slope, we chose a specific volume anomaly surface δ_{ref} as the reference level. The surface was chosen to divide the waters of subarctic origin (transported southwards by the California Current) from the northward flowing California Undercurrent waters. The California Current waters are characterized by the minimum in spiciness observed in the mean T/S-profile (found in the mean at σ_t=25.9, values between cruises varying from 25.6 and 26.1σ_t), while the California Undercurrent waters correspond to the subsurface maximum in spiciness (at σ_t= 26.3, with values varying from 26.2 to 26.5σ_t between cruises). Given this, we assume the geostrophic flow is close to zero at the intermediate surface σ_t=26.1 (Fig. 3). We used the specific volume anomaly surface corresponding to 26.1σ_t as the reference level δ_{ref} because (1) an exact geostrophic streamfunction exists for specific volume anomaly surfaces (the Montgomery streamfunction, while only an approximation exists for potential density surfaces; McDougall (1989)), and (2) specific volume anomaly gives a better approximation to a neutral surface than potential density (McDougall, 1987), resulting in a more accurate representation of the layer where horizontal motions occur. We calculated δ_{ref} by obtaining the mean temperature (Tref=10.1°C) and salinity (Sref=33.93 psu) on the 26.1 σ_t surface, and calculated the specific volume anomaly profiles for each cast:

$$\delta(p, S, T) = \frac{1}{\rho(p, S, T)} - \frac{1}{\rho(p, \mathrm{Sref}, \mathrm{Tref})}\,, \tag{1}$$

where $\rho(p, S, T)$ is the *in situ* density at pressure p, salinity S, and temperature T. A linear regression between σ_t and δ resulted in δ_{ref}=-8.67×10^{-9}m^{3}kg^{-1}. Using the average values of temperature and salinity near δ_{ref} makes it a better approximation to a neutral surface (McDougall, 1987). The geostrophic streamfunction Ψ at every station was estimated following a similar procedure to the one presented in Pérez-Brunius et al. (2004). First, dynamic height referenced to 10 dbar was calculated at every pressure level p down to the bottom of each cast:

$$\Phi(p) = -\int_{p}^{10\ \mathrm{dbar}} \delta(p', S, T)\, dp' \,. \tag{2}$$

Second, we obtained the Montgomery streamfunction at δ_{ref}, referenced to 10 dbar:

$$\Pi(\delta_{\mathrm{ref}}) = p_{\mathrm{ref}} \times \delta_{\mathrm{ref}} - \int_{p_{\mathrm{ref}}}^{10\ \mathrm{dbar}} \delta\, dp \,, \tag{3}$$

where p_{ref} is the pressure of the reference specific volume anomaly surface δ_{ref}. Finally, given the assumption that the geostrophic flow at δ_{ref} is zero, the final geostrophic streamfunction results in:

$$\Psi(p) = \frac{\Phi(p)}{f} - \frac{\Pi(\delta_{\mathrm{ref}})}{f} \,, \tag{4}$$

where f is the Coriolis parameter. Fig. 5 shows the maps of Ψ for each cruise at 30 dbar, illustrating the near surface geostrophic flow. Fig. 6 shows the depth of the reference surface δ_{ref}.

3 Results and Discussion

3.1 Coastal upwelling

Winds were upwelling favorable throughout the period studied here, and a clear seasonal cycle shows maximum values in late spring and summer, and near zero conditions in winter (Fig. 2). The upwelling season of spring and summer of 1999, 2002 and 2003 show anomalously high upwelling conditions, while 1998 corresponds to the weakest values. Even during the strong 1997-98 El Niño, upwelling favorable winds were present.

3.2 Thermohaline conditions

The different water masses of the California Current System are shown in Fig. 3 (e.g. Lynn & Simpson, 1987; Tomczak & Godfrey, 1994; Durazo & Baumgartner, 2002). Subarctic Water (SAW) originates in the Subarctic Front and is advected southwards by the California Current; North Equatorial Pacific Water (NEPW, or Equatorial Subsurface Water according to Durazo & Baumgartner (2002)) is brought from the Eastern Tropical Pacific by the California Undercurrent. North Pacific Central Water (NPCW, or Subtropical Surface Water according to Durazo & Baumgartner (2002)) is found on the eastern Suptropical Gyre, to the west of the California Current. The waters in the region of our study result from mixing of California Current SAW with waters found to the west (NPCW) and NEPW advected by the California Undercurrent (e.g. Lynn & Simpson, 1987; Chereskin & Niiler, 1994). The average T/S–profile shows the minimum in spiciness of the California Current waters (near 25.9σ_{t}) and the subsurface maximum characteristic of the California Undercurrent waters (near 26.3σ_{t}). The intermediate surface used as reference for the geostrophic velocity calculations ($\approx$26.1σ_{t}) is shown by the black contour. The boundaries for the water masses were adapted from Durazo & Baumgartner (2002). Our change in the upper salinity limit for SAW (33.6 rather than 34 psu as in Durazo & Baumgartner (2002)) reflects the conditions found near the Mexico-U.S.A. border (Badan-Dangon et al. (1989), also see Fig. 8 in Lynn & Simpson (1987)).

3.3 Geostrophic velocities

The geostrophic flow near the surface was consistently southwards except in August 1997 (Fig. 5), with no evidence of the Inshore Current near the coast of northern Baja California. An east-northeastward flow is found off San Diego in May 2001 and 2003, which could be the Ensenada Front near the shore. Maximum speeds at 30 dbar are ca. 25 to 35 cm s^{-1}, although in August 1997 speeds reach up to 60 cm s^{-1}. April 1998 follows with speeds close to 40 cm s^{-1}, and the lowest maximum speeds (less than 25 cm s^{-1}) were found in the June 2003 and May 2004 surveys.

The anomalous poleward flow found in August 1997 seems to be the extension of the near-surface coastal jet reported off the coast near 27.7°N by Durazo & Baumgartner (2002), responsible for the anomalously warm, salty, and light surface waters observed in Figs. 3 and 4. At 30 dbar, speeds were up to 60 cm s^{-1} near the Mexico-U.S.A. border, and around 35 cm s^{-1} in the southern part of the survey region. The reference surface δ_{ref} was very deep (180 to 210 dbar) at that time, and deepening towards the slope (Fig. 6). Poleward advection of southern waters were characteristic of the 1997-98 El Niño, but no poleward flow was observed during the 2002-04 El Niño, which also stands out for a shallow pycnocline, similar in depth from that observed in the previous La Niña surveys.

3.4 Effects of the 1997-98 El Niño

Although we recognize the risk of comparing data from cruises that did not take place during the same time of the year, the conditions observed in August 1997 and April 1998 clearly stand out from the rest, and are a consequence of the strong 1997-98 El Niño (McPhaden, 1999). August 1997 shows the spiciest and lightest waters near the surface (Fig. 4). Salinity sections in August 1997 (Fig. 7) show the offshore intrusion of salty waters above the fresh SAW, present in all the sections above 40 dbar. In fact, coastal upwelling was inhibited in August 1997, as can be seen by the downward tilting towards the continental slope of the deeper σ_t surfaces in most of the sections shown in Figs. 6 and 7, and by the presence near the coast of the fresh SAW. The geostrophic velocity field at 30 dbar shows northward flow only in August 1997, further supporting the idea of anomalous poleward advection in the region (Fig. 5). In fact, poleward transport was reported from April 1997 until February 1998 above 200 m and within 200-300 km from the coast north of San Diego (near 33°N), using hydrographic data from CALCOFI line 90 (Lynn & Bograd, 2002), with unusually spicy waters observed in July 1997. In addition, Durazo & Baumgartner (2002) observed very spicy surface waters south of Ensenada in the first two cruises of the IMECOCAL program, during October 1997 and January 1998. These conditions were attributed to the anomalous northward advection of NPCW from the Subtropical Gyre by a shallow coastal jet observed off Punta Eugenia (about 27.7°N). Our results corroborate the idea of a shallow surface jet transporting spicy waters off Punta Eugenia and into the Southern California Bight. Along the northwestern coast of Baja California, the jet was found above 40 dbar, its core as close as 20 kms from the coast, and mean speeds up to 20 cm s^{-1} at 30 dbar (referenced to δ_ref, which has a depth of 180-240 m). The waters carried by the August 1997 surface jet in our region of study are significantly fresher than the ones observed off Punta Eugenia in October 1997 and January 1998 (by .5 to 1 psu units), most likely the result of mixing on their northward path with the fresher SAW found offshore. Note that the surface jet waters are separated from the salty California Undercurrent waters by fresh Subarctic Water (Fig. 7). Hence, the surface poleward flow is not the result of surfacing of the California Undercurrent, and has most likely an offshore origin, as pointed out above. As a result, our data does not show evidence of an Inshore Current south of San Diego.

April 1998 was characterized by the spiciest waters in the density range $25<\sigma_t<26$, showing the presence of anomalously salty and warm waters at the level of the California Current (Figs. 3 and 4). This was also noted by Lynn & Bograd (2002) in the Southern California Bight, where record high spiciness and salinity values were observed in February 1998 on the $25.8\sigma_t$ surface within 200 km from the coast. Salty and cool water entered from below along the continental slope by upwelling (upward tilt of isopycnals, Fig. 8). These dense waters seem to have mixed diapycnally with the salty and warm surface waters brought by the poleward coastal jet observed in August 1997, resulting in a tongue of salty water that can be seen extending from the surface to the continental slope. It is this feature that results in the spicy waters observed at the California Current level. SAW is found both at subsurface offshore of the salty tongue, as well as trapped inshore of the tongue. This peculiar setup is found more clearly on the two southernmost sections, although the sections north of the Coronado Islands (32.42°N) also show evidence of it. Note that the near-surface geostrophic velocities suggest southward flow at the time (Fig. 5). Winter cooling of the warm and spicy surface waters brought to the region by the poleward surface jet would increase their density to the layer of the SAW, where the mixing of the two waters would partially explain the high salinity observed in the April 1998 mixed layer. But some other process must have caused the cross-pycnocline mixing with the subsurface salty waters. We explored the possibility of shear instability of the stratified geostrophic flow as a possible cause for the strong diapycnal mixing observed. The geostrophic gradient Richardson number was calculated on each transect of every cruise:

$$Ri_g = \frac{N^2}{(\frac{g}{\rho f}\frac{\delta \rho}{\delta x})^2} \tag{5}$$

where N^2 is the Brunt-Väisälä frequency, g is the acceleration of gravity, ρ is the *in situ* density, f the local Coriolis parameter, and x distance along the transect. This number serves as a criterion for the linear stability of the geostrophic flow, which is guaranteed for $Ri_g > 1$ (reported critical values vary between 0.25 and 1.0 (Kundu, 1990; van Gastel & Pelegri, 2004)). Our values are generally higher than 1.5. A few sections had small regions in the upper 20 dbar where Ri_g is close to the critical value, and April 1998 does not stand out from the rest as a candidate for shear instability, at least not by the geostrophic flow. Of course, using the geostrophic shear for the gradient Richardson number does not take into account several other motions that may lead to shear instability, whether they are large-scale ageostrophic components inherent to the current, or small scale ageostrophic motions (e.g. internal waves) which could certainly give raise to subcritical conditions. In fact, the strong motions common in the continental slope and shelf, induced by coastally trapped waves, upwelling, tidal forcing and internal waves could contribute with significant energy for the observed mixing. It is common to see intrusions of salty subsurface waters across isopycnals in the upwelling conditions found during the La Niña surveys of May-June 2001 to 2002 (Fig. 9 shows an example). These intrusions result in the high and near constant salinities observed for σ_{t}<25.5 in the 2001-03 cruises. But in those cases, upwelled waters reach the surface near the shelf break, moving offshore as they mix with the lighter and fresher offshore waters, hence raising the salinity of the near surface layers. What is rare in the April 1998 case is the trapped surface core of SAW near the coast, suggesting that the salty subsurface waters mixed across the pycnoline from below.

April 1999 shows the coldest and densest surface waters recorded in the data presented here. This agrees with what would be expected during the cold La Niña conditions that started in mid-1998 and were felt until early 2001 in the North Pacific (McPhaden, 2004). Indeed, spring and summer of 1999 were marked by strong negative sea surface temperature anomalies off central and northern California, although off Baja California the hydrographic anomalies observed by the IMECOCAL surveys were relatively small (Bograd et al., 2000). Since then, the most remarkable change in the thermohaline properties of the upper hundred meters of the water column is the freshening that has taken place since May 2002, suggesting a stronger influence of the SAW in the shelf and slope region (Figs. 4 and 10). Given that we have been in a moderate El Niño phase since mid-2002 (McPhaden, 2004; Wolter, 2005), these are unexpected results: El Niño conditions would suggest a weakened California Current and stronger presence of the salty California Undercurrent waters. Moreover, strong upwelling conditions during 2003 would suggest the presence of salty California Undercurrent waters in the surface layer. Instead, the large presence of SAW near the coast at this time results in anomalously fresh conditions for the top 100 dbar. The observed conditions look conspicuously similar to the ones reported in the California Current System from

July 2002 until April 2003. Record low temperature and salinities were observed from British Columbia (49°N) to the middle of the Baja California peninsula (28°N), associated to an anomalous intrusion of Subarctic Water from the Gulf of Alaska (Venrick et al., 2003; Huyer, 2003; Bograd & Lynn, 2003; Freeland et al., 2003; Durazo et al., 2005). The intrusion overshadowed the effects of the El Niño in the region. Off Southern California, Bograd & Lynn (2003) located the core of the anomalous fresh and cold water in July 2002 at 175 m depth, 150-200 km from Point Conception ($\approx$ 34.5°N). Durazo et al. (2005) reported the largest fresh and cold anomaly between 100 and 150 m in April 2003, in a core centered 50 km from the continental slope off Punta Eugenia ($\approx$ 28°N), with signs of the SAW intrusion already observed in October 2002. Our results show that waters of low spiciness were present within 30 km of the coast of northern Baja California in May 2003, and that the waters by May 2004 have continued to cool and freshen. From April 1998 to May 2004, the $25.3\sigma_{\mathrm{t}}$ surface at the 32.08°N section has shown a salinity decrease close to 0.4 psu units and a cooling of more than 1.5°C, resulting in a -0.6 spiciness change. Conditions past April 2003 have not yet been reported, but our results suggest that the anomalous intrusion of the SAW has continued to influence the waters off Baja California at least until May 2004.

Put in a broader context, the sustained cooling and freshening of the near surface waters observed since 2002 may be related to a climate shift that could have occured in 1998-99. Although too early to tell, a switch from a "warm" to "cold" Pacific Decadal Oscillation (PDO) phase may have taken place at the end of the 1997-98 El Niño (e.g. Hare & Mantua, 2000; Venrick et al., 2003; Peterson & Schwing, 2003). A long-lived El Niño-like pattern of Pacific climate variability, the PDO switches phases every 20 to 30 years, most recently in 1976-77 (Mantua & Hare, 2002). Among the physical effects expected during a cold PDO phase are: more and stronger La Niña events with few and weak El Niños; weak cyclonic wind stress over the northeastern Pacific; and a increase in coastal upwelling over the North American coast (Mantua, 2005). In addition to the cyclonic wind stress anomaly observed over the northeastern Pacific, the 1999-03 period stands out for anomalous anticyclonic wind stress over the subarctic North Pacific (Peterson & Schwing, 2003). This pattern may have caused the intrusion of the cold and fresh waters into the California Current System observed since 2002, by a combined effect of anomalous southward Ekman transport of waters into the North Pacific Current and a strong eastward flow of this current towards the North American coast (Murphree et al., 2003).

3.6 Stratification changes

The stratification of the water column (measured by the difference between the potential density at 10 dbar and 50 dbar, Fig. 11) has been increasing more or less steadily since the 1997-98 El Niño. In the latter years, this is mostly due to an increasingly larger difference between the temperatures at the two levels, and is a result both of warming of the surface waters and the enhanced presence of cold and fresh Subarctic Waters below 20 dbar. We note that these changes in stratification are typical for all the transects analyzed, although we only show the results for 32.08°N.

4 Summary

Summarizing the results from the analysis of hydrographic data collected between 1997-04 on the continental shelf and slope region of northwestern Baja California:

(1) Geostrophic velocities (referenced to $\delta_{\mathrm{ref}} \approx 26.1\sigma_{\mathrm{t}}$) suggest southward surface flow (maximum speeds around 30 cm s^{-1} at 30 dbar) south of Tijuana in all cruises except in the anomalous El Niño conditions found in August 1997, when a poleward surface jet carried anomalous salty and warm waters into the region. This jet is probably the nearshore expression of the anomalous northward flow reported off Punta Eugenia (about 27.7°N, Durazo & Baumgartner (2002)) and Southern California (Lynn & Bograd, 2002) during the 1997-98 El Niño. Given its high salinity and temperature, Durazo & Baumgartner (2002) suggest it originated in the Eastern Subtropical Pacific, entering the

region southwest of Punta Eugenia. In addition, the jet was separated from the California Undercurrent waters by a pool of Subarctic Water, and hence this poleward flow was not due to surfacing of the California Undercurrent. No evidence of an Inshore Current was found south of Tijuana on our surveys, suggesting that a surface counter current is not a common feature off northern Baja California.

(2) Very spicy conditions were found on the isopycnals corresponding to the fresh California Current waters ($25<\sigma_t<26$) in April 1998. We attribute this to mixing across the pycnocline between the salty surface waters advected by the 1997-98 El Niño jet and the California Undercurrent waters below, which diluted the fresh Subarctic Waters found between the two in August 1997. Shear instability by the geostrophic current did not seem to have triggered the cross-isopycnal mixing. Most likely, other processes common to the continental shelf and slope region (coastally trapped waves, tidally generated internal waves, upwelling) may have contributed the energy needed for the mixing observed.

(3) Since May-June 2002, the waters between 20 and 100 dbars have been getting progressively fresher and colder, despite the positive El Niño phase. This seems to show the presence near the northern Baja California coast of the anomalous intrusion of Subarctic water reported from July 2002 until April of 2003 more

than 50-100 km offshore Southern California and Punta Eugenia (Bograd & Lynn, 2003; Durazo et al., 2005). Our results suggest that the anomalous inflow of Subarctic waters has continued at least until May-June of 2004.

(4) Stratification in late spring has been increasing since April 1999, with the largest changes observed after May 2002. This is mainly due to a combination of surface warming and the strong presence below 20 dbar of progressively colder and fresher Subarctic Water.

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References

Alvarez, L. G., Durazo, R., Pérez, J., Navarro, L. F., & Hernández, R. (1984). Observaciones de corrientes costeras superficiales mediante trazadores Lagrangeanos II. Eréndira, Baja California, 1979-1981. Unpublished report, Depto. Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México. In Spanish.

Alvarez, L. G., Godínez, V. M., & Lavín, M. F. (1990). Near-shore dispersion off Tijuana, Baja California. Ciencias Marinas, 16, 87–109.

Badan-Dangon, A., Robles, J. M., & Garcia, J. (1989). Poleward flows off Mexico's Pacific coast. In S. J. Neshyba, C. N. K. Mooers, R. L. Smith, & R. T. Barber. (Eds.), Poleward flows along eastern ocean boundaries. Springer-Verlag, New York, USA. pp. 176–202.

Bakun, A. (1973). Coastal upwelling indices, west coast of North America, 1946-71. NOAA technical report NMFS SSRF–671, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Seattle, USA.

Bakun, A. & Nelson, C. S. (1977). Climatology of upwelling related processes off Baja California. CalCOFI Report, 19, 107–127.

Barton, E. D. & Argote, M. L. (1980). Hydrographic variability in an upwelling area off Northern Baja California in June, 1976. Journal of Marine Research, 38, 631–649.

Barton, E. D., Robles, J. M., Amador, A., & Morales, C. (1980). A year of current and temperature observations off Baja California North. Data report, Depto. Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México.

Bograd, S., DiGiacomo, P., Durazo, R., Hayward, T., K.D.Hyrenbach, Lynn, R., Mantyla, A., Schwing, F., Sydeman, W., Baumgartner, T., Lavaniegos, B., & Moore, C. (2000). The state of the California Current in 1999-2000: Forward to a new regime? CalCOFl Reports, 41, 26–52.

Bograd, S. J. & Lynn, R. J. (2003). Anomalous subarctic influence in the southern California Current during 2002. Geophysical Research Letters, 30, 8020.

Chelton, D. B. (1982). Large-scale response of the California Current to forcing by the wind stress curl. CalCOFI Report, 23, 130–148.

Chereskin, T. & Niiler, P. (1994). Circulation in the Ensenada Front-September 1988. Deep-Sea Research I, 41, 1251–1287.

Collins, C., Castro, C., Asanuma, H., Rago, T., Han, S.-K., Durazo, R., & Chavez, F. (2002). Changes in the hydrography of Central California waters associated with the 1997-98 El Niño. Progress in Oceanography, 54, 129–147.

Durazo, R. & Baumgartner, T. (2002). Evolution of oceanographic conditions off Baja California: 1997-1999. Progress in Oceanography, 54, 7–31.

Durazo, R., Baumgartner, T., Bograd, S., Collins, C., de la Campa, S., Garcia, J., Gaxiola-Castro, G., Huyer, A., Hyrenbach, K., Loya, D., Lynn, R., Schwing, F., Smith, R., Sydeman, W., & Wheeler, P. (2001). The state of the California Current, 2000-2001: A third straight La Niña year. CalCOFl Reports, 42, 29–60.

Durazo, R., Gaxiola-Castro, G., Lavaniegos, B. E., Castro-Valdéz, R., Valdés, J. G., & Mascarenhas Jr., A. S. (2005). Oceanographic conditions west of the Baja California coast 2002-2003: A weak El Niño and Subarctic water enhancement. Ciencias Marinas. In Press.

Espinosa-Carreon, T. L., Strub, P. T., Beier, E., Ocampo-Torres, F., & Gaxiola-Castro, G. (2004). Seasonal and interannual variability of satellite-derived chlorophyll pigment, surface height, and temperature off Baja California. Journal of Geophysical Research, 109, C03039. doi:10.1029/2003JC002105.

Flament, P. (2002). A state variable for characterizing water masses and their diffusive stability: spiciness. Progress in Oceanography, 54, 493–501.

Fofonoff, N. P. & Millard, R. C. (1983). Algorithms for computation of fundamental properties of seawater. UNESCO Technical Papers in Marine Science, 44, 15–23.

Freeland, H. J., Gatien, G., Huyer, A., & Smith, R. L. (2003). Cold halocline in the northern California Current: an invasion of subarctic water. Geophysical Research Letters, 30, 1141.

García-Córdova, J., López-Mariscal, M., Pineda, J., & Pérez-Brunius, P. (2004). Hidrografía en las costas oeste de California y Baja California. Campaña

NOHYPE-1. R/V Gordon Sproul. Mayo 10-23 de 2001. Technical report, Depto. Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México. In Spanish.

Hare, S. R. & Mantua, N. J. (2000). Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47, 103–146.

Haury, L. R., Venrick, E. L., Fey, C. L., McGowan, J. A., & Niiler, P. P. (1993). The Ensenada Front: July 1985. CalCOFI Report, 34, 69–88.

Huyer, A. (1983). Coastal upwelling in the California Current System. Progress in Oceanography, 12, 259–284.

Huyer, A. (2003). Preface to special section on enhanced subarctic influence in the California Current, 2002. Geophysical Research Letters, 30, 8019.

Kundu, P. K. (1990). Fluid mechanics. Academic Press, San Diego, USA, 1st. edition. 638 pp.

Lynn, R. (1967). Seasonal variation of temperature and salinity at 10 meters in the California Current. CalCOFl Reports, 11, 157–186.

Lynn, R. & Bograd, S. (2002). Dynamic evolution of the 1997-1999 El Niño - La Niña cycle in the southern California Current System. Progress in Oceanography, 54, 59–75.

Lynn, R., Bograd, S., Chereskin, T., & Huyer, A. (2003). Seasonal renewal of the California Current: The spring transition off California. Journal of Geophysical

Research, 108, 3279.

Lynn, R. & Simpson, J. (1987). The California Current System: The seasonal variability of its physical characteristics. Journal of Geophysical Research, 92, 12,947–12,966.

Mantua, N. (2005). The Pacific Decadal Oscillation. WWW Page, http://www.atmos.washington.edu/ mantua/REPORTS/PDO/PDO_egec.htm. To appear in the Encyclopedia of Global Environmental Change.

Mantua, N. J. & Hare, S. R. (2002). The Pacific Decadal Oscillation. Journal of Oceanography, 58, 35–44.

McDougall, T. J. (1987). Neutral surfaces. Journal of Physical Oceanography, 17, 1950–1964.

McDougall, T. J. (1989). Streamfunctions for the lateral velocity vector in a compressible ocean. Journal of Marine Research, 47, 267–284.

McPhaden, M. (1999). Genesis and evolution of the 1997-98 El Niño. Science, 283, 950–954.

McPhaden, M. (2004). Evolution of the 2002/03 El Niño. Bulletin of the American Meteorological Society, 85, 677–695. doi: 10.1175/BAMS-85-5-677.

Murphree, T., Bograd, S. J., Schwing, F. B., & Ford, B. (2003). Large scale atmosphere-ocean anomalies in the northeast Pacific during 2002. Geophysical Research Letters, 30, 8026.

Pares-Sierra, A. & O'Brien, J. (1989). The seasonal and interannual variability of the California Current System: A numerical model. Journal of Geophysical Research, 94, 3159–3180.

Pelaez, J. & McGowan, J. A. (1986). Phytoplankton pigment patterns in the California Current as determined by satellite. Limnology and Oceanography, 31, 927–950.

Pérez-Brunius, P., García-Córdova, J., López-Mariscal, M., & Pineda, J. (2004a). CTD Data Report, Cruise NOHYPE II (Nearshore-Offshore Hydrodynamics and Population Ecology). May 24-June 4, 2002. Technical report, Depto. Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México.

Pérez-Brunius, P., López-Mariscal, M., García-Córdova, J., & Pineda, J. (2004b). CTD Data Report, Cruise NOHYPE III (Nearshore-Offshore Hydrodynamics and Population Ecology). June 8-18, 2003. Technical report, Depto. Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México.

Pérez-Brunius, P., López-Mariscal, M., García-Córdova, J., & Pineda, J. (2004c). CTD Data Report, Cruise NOHYPE IV (Nearshore-Offshore Hydrodynamics and Population Ecology). May 25-June 4, 2004. Technical report, Depto. Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, México.

Pérez-Brunius, P., Rossby, T., & Watts, R. D. (2004). Absolute transports of mass and temperature for the North Atlantic Current-Subpolar Front system. Journal of Physical Oceanography, 34, 1870–1883.

Peterson, W. T. & Schwing, F. B. (2003). A new climate regime in northeast Pacific ecosystems. Geophysical Research Letters, 30, 1896.

PFEL (2005). Pacific Fisheries Environmental Laboratory Coastal Upwelling Indices. Data set, http://www.pfeg.noaa.gov/products/PFEL/PFEL.html.

Pierce, S., Smith, R., Kosro, P., Barth, J., & Wilson, C. (2000). Continuity of the poleward undercurrent along the eastern boundary of the mid-latitude North Pacific. Deep-Sea Research II, 47, 811–829.

Pineda, J., Gutiérrez de Velasco, G., Herrera, H., & Smith, D. W. (1997). CTD Data report. Cruise LARBAJA I. 20–26 August 1997. R/V Robert Gordon Sproul. Technical report, Woods Hole Oceanographic Institution, Woods Hole, USA.

Pineda, J., Gutiérrez de Velasco, G., Herrera, H., & Smith, D. W. (1998a). CTD Data report. Cruise LARBAJA II. 4–9 April 1998. R/V Robert Gordon Sproul. Technical report, Woods Hole Oceanographic Institution, Woods Hole, USA.

Pineda, J., Gutiérrez de Velasco, G., Herrera, H., & Smith, D. W. (1998b). CTD Data report. Cruise LARBAJA III. 3–7 August 1998. R/V Robert Gordon

Sproul. Technical report, Woods Hole Oceanographic Institution, Woods Hole, USA.

Pineda, J., Gutiérrez de Velasco, G., Herrera, H., & Smith, D. W. (1999). CTD Data report. Cruise LARBAJA IV. 7–12 April 1999, R/V Robert Gordon Sproul. Technical report, Woods Hole Oceanographic Institution, Woods Hole, USA.

Pineda, J. & López, M. (2002). Temperature, stratification and barnacle larval settlement in two Californian sites. Continental Shelf Research, 22, 1183–1198.

Reid, J., Schwarzlose, R. A., & Brown, D. M. (1963). Direct measurements of a small surface eddy off northern Baja California. Journal of Marine Research, 21, 205–218.

Schwing, F., Bograd, S., Collins, C., Gaxiola-Castro, G., Garca, J., Goericke, R., Gomz-Valdz, J., Huyer, A., Hyrenbach, K., Kosro, P., Lavaniegos, B., Lynn, R., Mantyla, A., Ohman, M. D., Peterson, W., Smith, R., Sydeman, W., Venrick, E., & Wheeler, P. (2002). The state of the California Current, 2001-2002: Will the California Current System keep its cool, or is El Niño looming? CalCOFI Rep., 43, 31–68.

Strub, P. & James, C. (2000). Altimeter-derived variability of surface velocities in the California Current System: 2. Seasonal circulation and eddy statistics. Deep-Sea Research II, 47, 831–870.

Tapia, F. J., Pineda, J., Ocampo-Torres, F. J., Fuchs, H. L., Parnell, P. E., Montero, P., & Ramos, S. (2004). High-frequency observations of wind-forced onshore transport at a coastal site in Baja California. Continental Shelf Research, 24, 1573–1585.

Tisch, T., Ramp, S., & Collins, C. (1992). Observations of the geostrophic current and water mass characteristics off Point Sur, California, from May 1988 through November 1989. Journal of Geophysical Research, 97(C8), 12,535–12,555.

Tomczak, M. & Godfrey, S. J. (1994). Regional Oceanography: An Introduction. Elsevier Science Ltd., London, Great Britain, 1st edition. 422 pp.

van Gastel, P. & Pelegri, J. P. (2004). Estimates of gradient Richardsons numbers from vertically smoothed data in the Gulf Stream region. Ciencias Marinas, 68, 459–482.

Venrick, E., Bograd, S., Checkley, D., Durazo, R., Gaxiola-Castro, G., Hunter, J., Huyer, A., Hyrenbach, K. D., Lavaniegos, B. E., Mantyla, A., Schwing, F. B., Smith, R. L., Sydeman, W. J., & Wheeler, P. A. (2003). The state of the California Current in 2002-2003: Tropical and Subarctic influences vie for dominance. CalCOFl Reports, 44, 28–60.

Wolter, K. (2005). Multivariate ENSO index (MEI). WWW Page, http://www.cdc.noaa.gov/people/klaus.wolter/MEI/.

Wooster, W. S. & Jones, J. H. (1970). California Undercurrent off Northern Baja California. Journal of Marine Research, 28, 235–250.

Wyllie, J. (1966). Geostrophic flow of the California Current at the surface and 200 m. In CalCOFI Atlas 4 (pp. 48 and 288 charts). Scripps Institution of Oceanography, San Diego, USA.

Figure captions

Figure 1. Hydrographic stations taken in the region between La Jolla, California, and Salsipuedes, Baja California. Black circles show stations taken during the LARBAJA campaigns. Dark gray circles show the 2001 NO-HYPE cruise stations, while the light gray squares show the ones taken during the 2002-04 NO-HYPE campaigns. Bathymetric contours: 25, 100, 250, 500, 750, 1000, and 1500 dbar.

Figure 2. Coastal Upwelling Index at 31.5°N, 119°W. Units are m^3s^{-1} per 100 m coastline. The solid line represents the monthly mean, the dashed line shows the 53 year climatological monthly mean, filled circles show the conditions at the time of the hydrographic cruises analyzed in this article. Upwelling occured thoughout the period shown, with near zero values in the winter months, maximum transports in late spring and summer.

Figure 3. T/S diagram for the hydrographic data used in this study. Data shown at 5 dbar intervals. The August 1997, April 1998, and May 2004 data are highlighted, to show the anomalously warm and salty conditions found during the 1997-98 El Niño as well as the anomalously fresh near-surface waters found in the most recent cruise. The data from the rest of the cruises are represented by the light gray points. Isolines of spiciness (dashed) and σ_t (continuous) are shown by light gray contours. The black curves show the mean T/S–profile ($\sigma_t \in [24.5, 27]$) with one standard

deviation. The 26.1σ_t surface is shown as the thick black contour, it corresponds to the reference surface δ_{ref} used for the geostrophic velocity calculations. Boundaries of the water masses discussed in the text were adapted from Durazo & Baumgartner (2002); Lynn & Simpson (1987) and Tomczak & Godfrey (1994): NPCW–North Pacific Central Water, SAW– Subarctic Water, NPEW– North Pacific Equatorial Water, TSW- Tropical Surface Water.

Figure 4. Mean T/S–profiles ($\sigma_t \geq 27$) for the data of each of the cruises, shown to compare the different conditions observed during El Niño 1997-98, La Niña 1999-02, and the weak El Niño that followed. Stars show the 20 dbar level, while filled circles denote 100 dbars. Light gray contours show isolines of spiciness (dashed) and σ_t (continuous), the bold black contour shows the 26.1σ_t surface, corresponding approximately to the reference surface δ_{ref} used for the geostrophic velocities calculations.

Figure 5. Geostrophic streamfunction at 30 dbar, referenced to δ_{ref}=-8.67$\times 10^{-9}$m^{3}kg^{-1} ($\approx$ 26.1σ_t). Contours are shown every 5$\times 10^2$m^{2}s^{-1}, arrows indicate the direction of flow. Note that the flow is southwards except during August 1997. In May 2001 and June 2003 there is east-northeastward flow off San Diego, probably the result of a southward extension of the Southern California Eddy.

Figure 6. Pressure of the δ_{ref}=-8.67$\times 10^{-9}$m^{3}kg^{-1} ($\approx$ 26.1σ_t) surface. Contours

are shown every 10 dbar.

Figure 7. Salinity sections perpendicular to the coast, showing the salty near surface (< 40 dbar) coastal jet observed in August 1997. Salinity units are psu. Note the fresh Subarctic Water below the coastal jet, as well as signs of the salty California Undercurrent water found at depths below 100 dbar. Contours show σ_t surfaces spaced by 0.2 units, the bold contour denotes the 24.8 and $25.9\sigma_\mathrm{t}$ surfaces.

Figure 8. Salinity (psu) sections perpendicular to the coast in April 1998, showing the result of cross-isopycnal mixing between the surface jet observed in Figure 7 and the salty California Undercurrent waters below. Signs of fresh Subarctic Water can be seen at both sides of the salty intrusion: at the surface by the coast, and at subsurface offshore. The southernmost sections show stronger presence of the Subarctic Water. Contours show σ_t surfaces spaced by 0.2 units, the bold contours denote the 24.8 and $25.9\sigma_\mathrm{t}$ surfaces.

Figure 9. Salinity section at 32.05°N, May 2002, showing the results of an upwelling event. Note the salty water brought up to the surface along the continental slope, and then pushed offshore above the fresh Subarctic Water core. Contours show σ_t surfaces spaced by 0.2 units, the bold contours denote the 24.8, 25.9, and $26.1\sigma_\mathrm{t}$ surfaces.

Figure 10. Mean salinity, temperature, and spiciness on σ_t=25.3 kg m^{-3} along the section at 32.08°N. Dashed lines represent one standard deviation. Note the change to fresher and colder conditions since May 2002.

Figure 11. Difference between the mean salinity, temperature, and potential density at 10 and 50 dbar on the 32.08°N section. Dashed lines show standard deviation. Note that the stratification has steadily increased mainly due to a larger temperature difference between the two levels.

Cruise name	Dates
LARBAJA I	August 20-26, 1997
LARBAJA II	April 4-9, 1998
LARBAJA III	August 3-7, 1998
LARBAJA IV	April 7-12, 1999
NO-HYPE I	May 10-21, 2001
NO-HYPE II	May 24-June 3, 2002
NO-HYPE III	June 8-18, 2003
NO-HYPE IV	May 25-June 4, 2004

Table 1
Dates for the Larvae in Alta and Baja California (LARBAJA) and Nearshore-Offshore Hydrodynamics and Population Ecology (NO-HYPE) cruises that collected the hydrographic data used in this study.

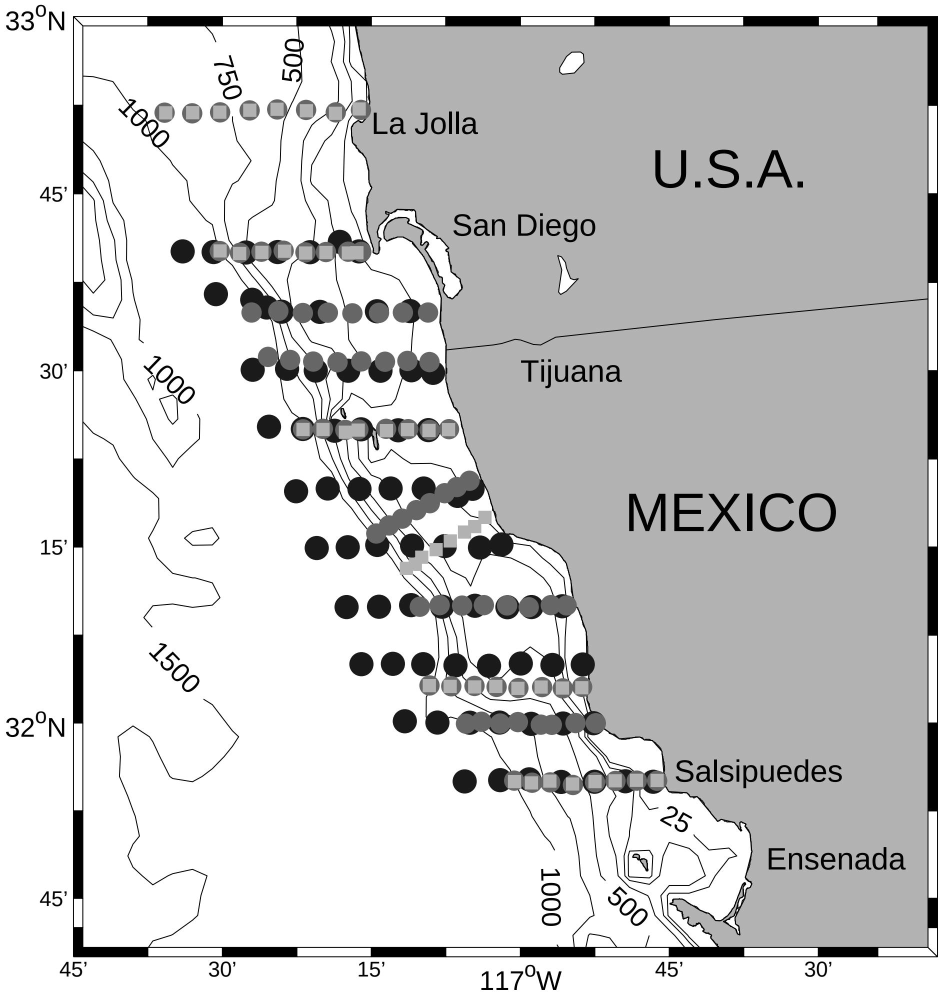

33°N
45'
30'
15'
32°N
45'
45'
30'
15'
117°W
45'
30'
750
500
1000
1000
1500
1000
500
25
La Jolla
U.S.A.
San Diego
Tijuana
MEXICO
Salsipuedes
Ensenada

Fig. 1.

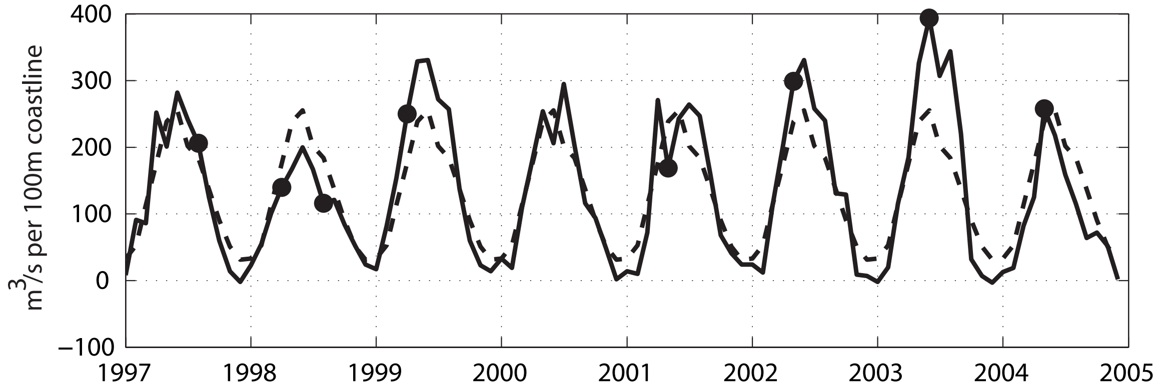

400
300
200
100
0
−100
1997
1998
1999
2000
2001
2002
2003
2004
2005
m^3/s per 100m coastline

Fig. 2.

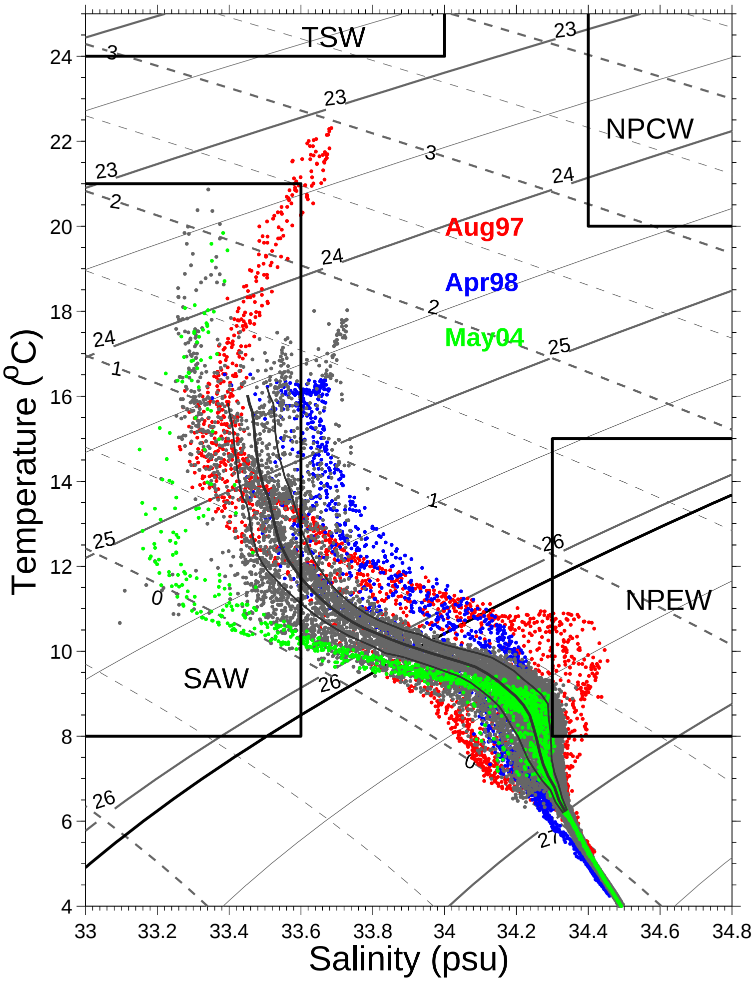

TSW
NPCW
Aug97
Apr98
May04
NPEW
SAW
Temperature (°C)
Salinity (psu)

Fig. 3.

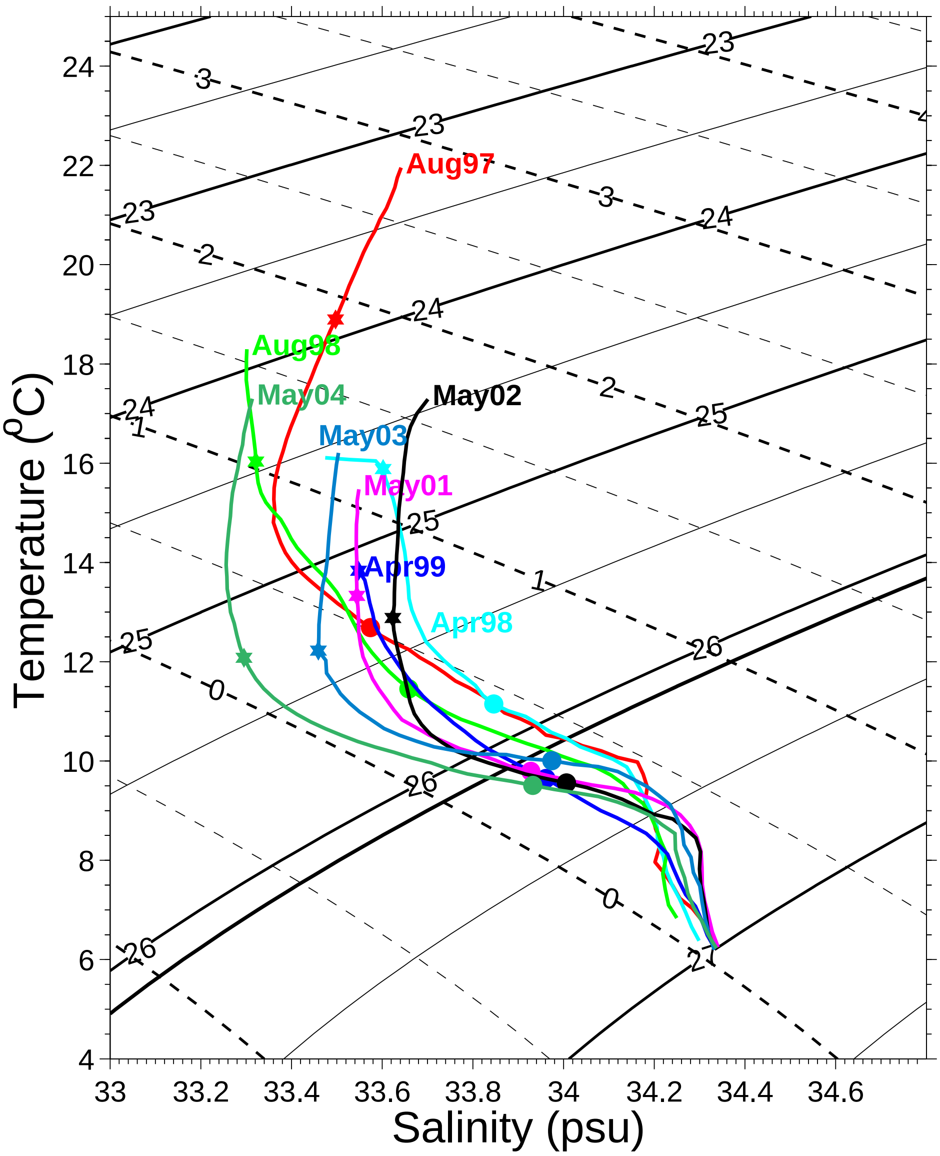

Aug97
Aug98
May04
May02
May03
May01
Apr99
Apr98
Temperature (°C)
Salinity (psu)

Fig. 4.

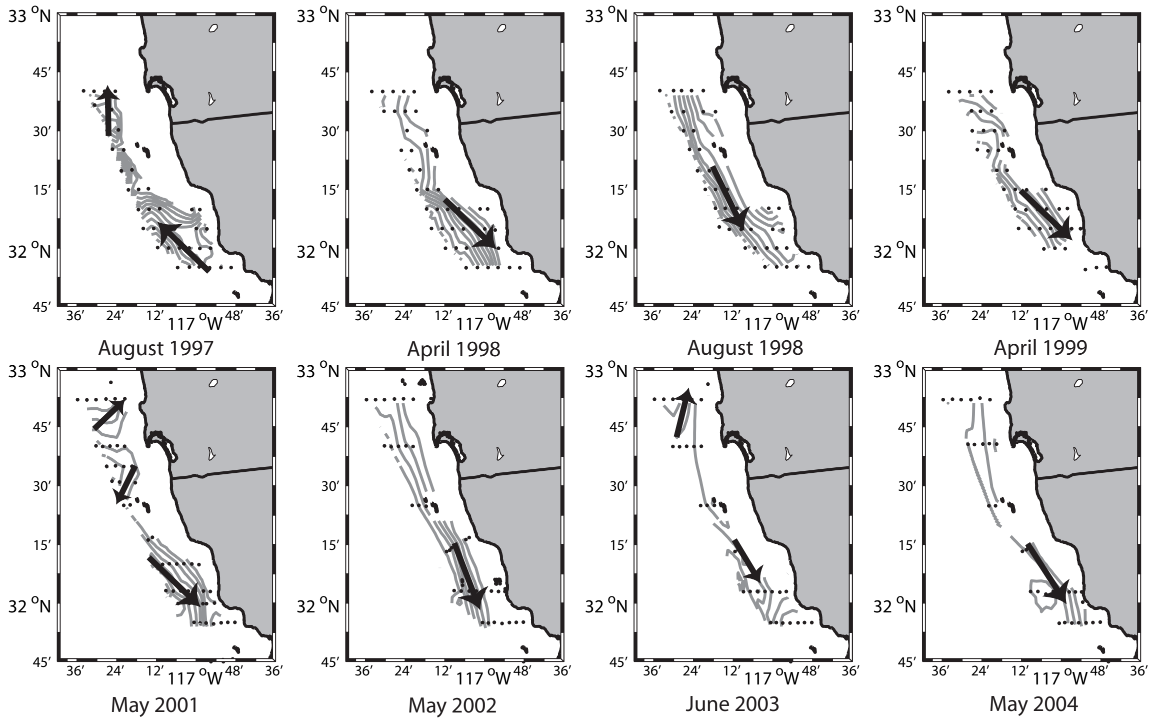

August 1997
April 1998
August 1998
April 1999
May 2001
May 2002
June 2003
May 2004
33 °N
45′
30′
15′
32 °N
45′
36′
24′
12′
117 °W
48′
36′

Fig. 5.

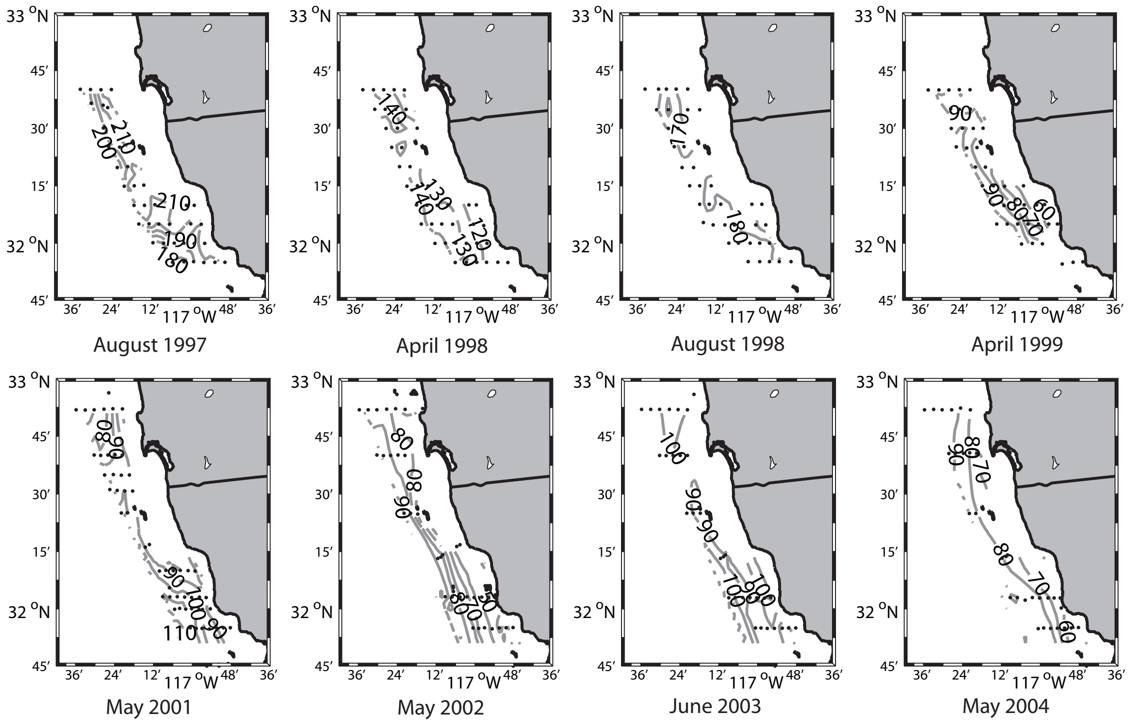
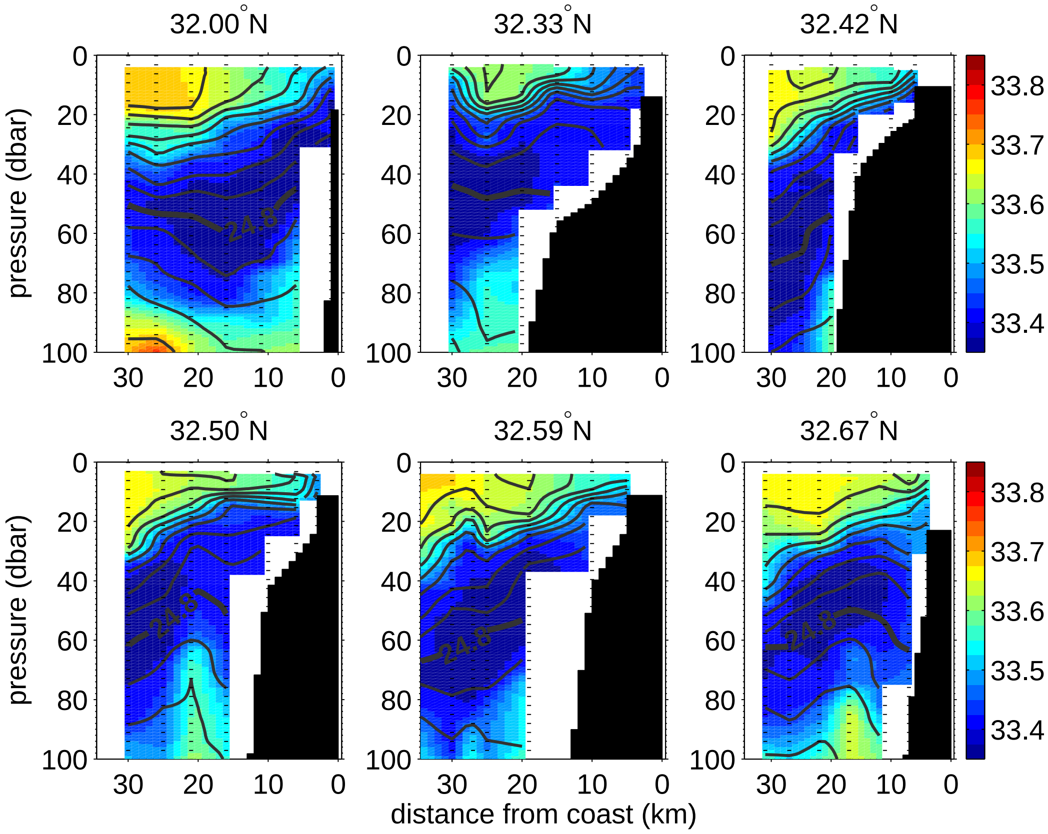

August 1997
April 1998
August 1998
April 1999
May 2001
May 2002
June 2003
May 2004

Fig. 6.



32.00°N
32.33°N
32.42°N
32.50°N
32.59°N
32.67°N
pressure (dbar)
distance from coast (km)
24.8
0
20
40
60
80
100
30
20
10
0
33.8
33.7
33.6
33.5
33.4

Fig. 7.

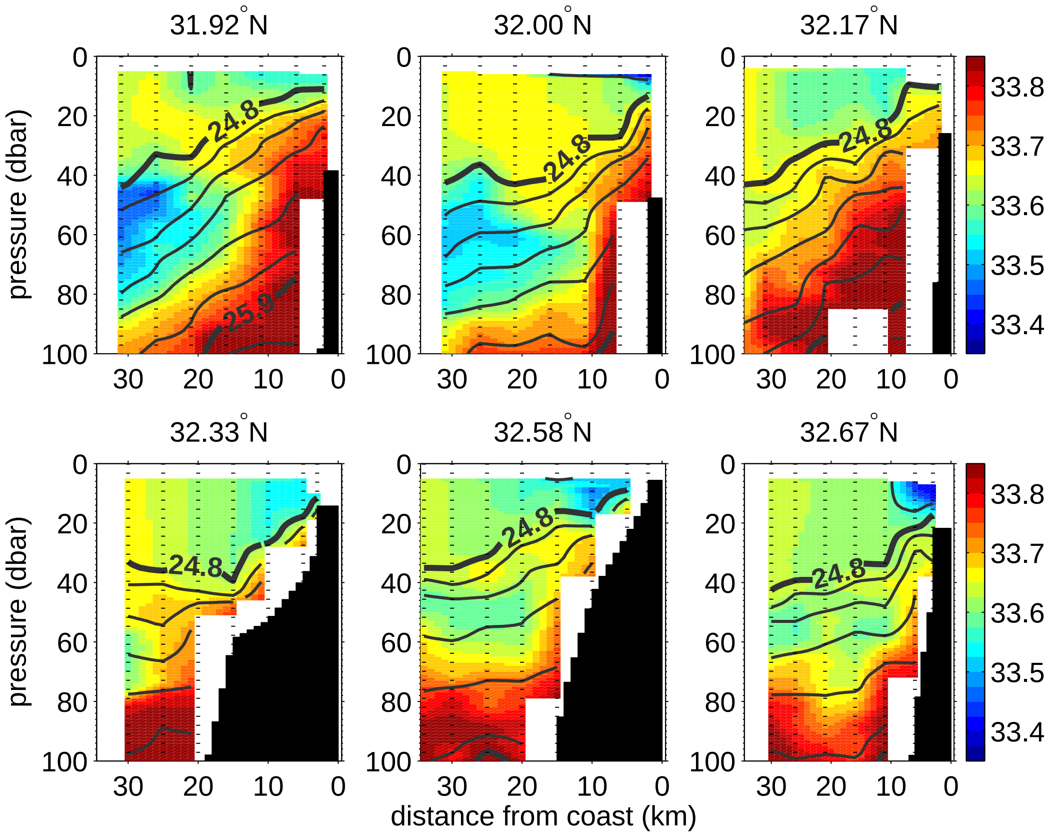
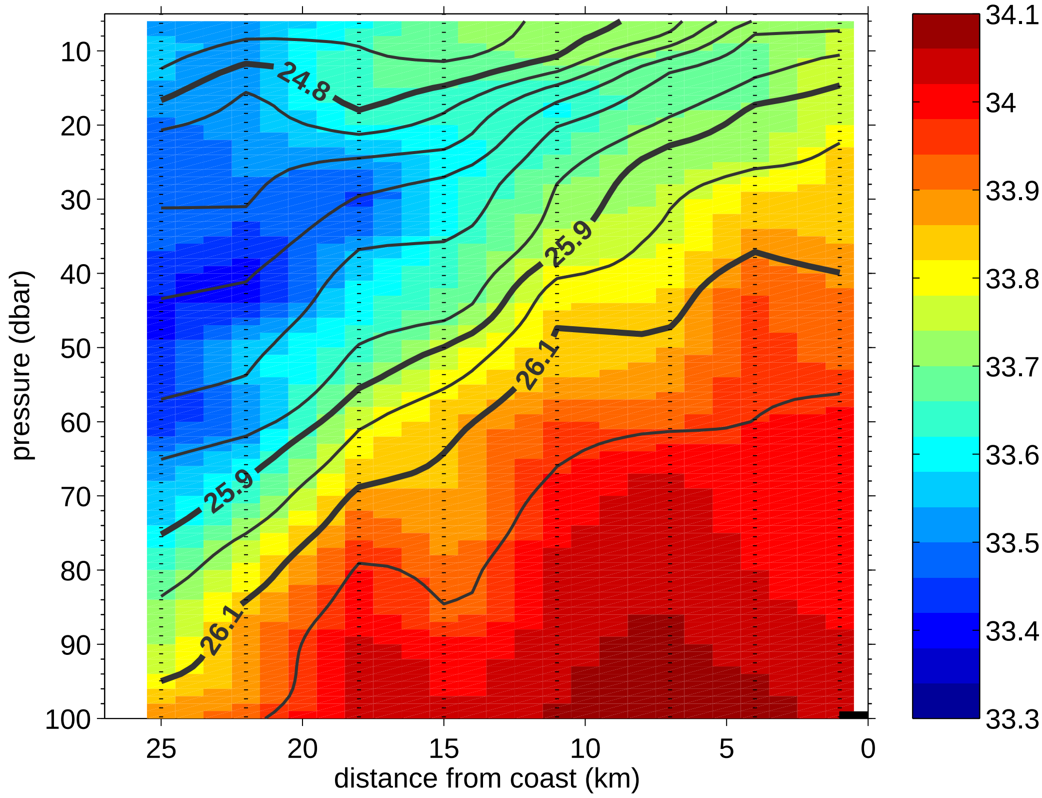

31.92°N
32.00°N
32.17°N
32.33°N
32.58°N
32.67°N
pressure (dbar)
distance from coast (km)
24.8
25.9
33.8
33.7
33.6
33.5
33.4

Fig. 8.



34.1
34
33.9
33.8
33.7
33.6
33.5
33.4
33.3
24.8
25.9
25.9
26.1
26.1
10
20
30
40
50
60
70
80
90
100
pressure (dbar)
25
20
15
10
5
0
distance from coast (km)

Fig. 9.

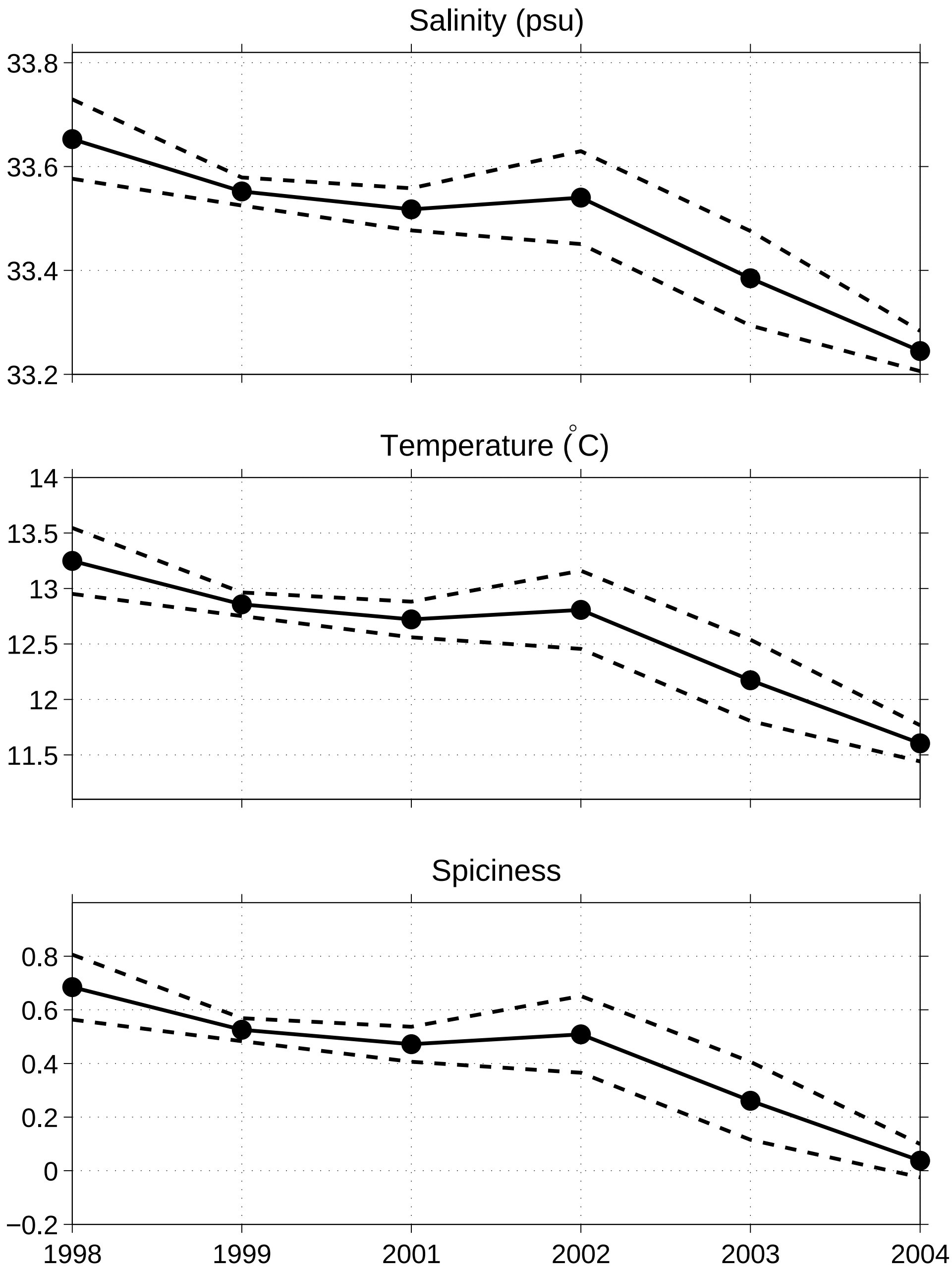
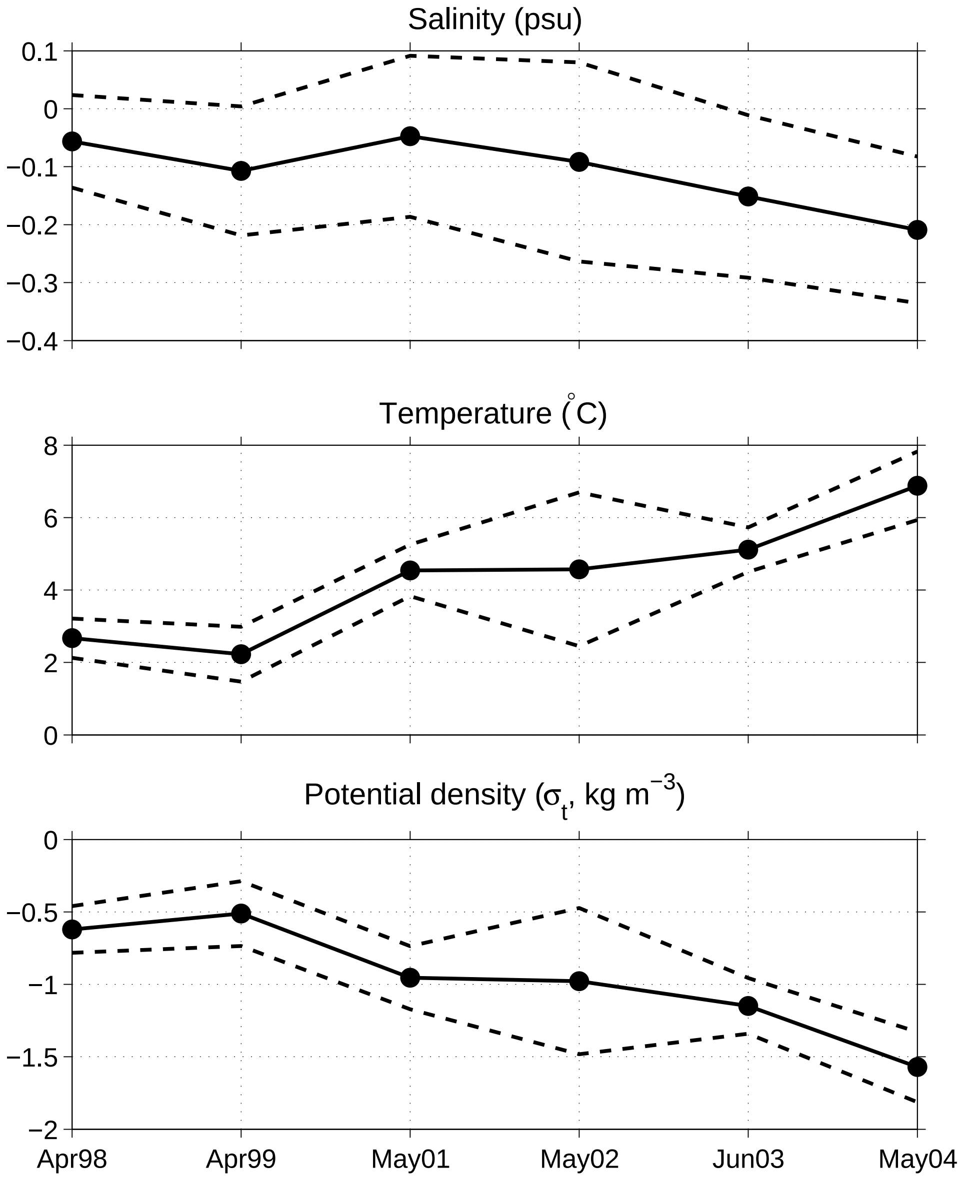

Salinity (psu)
33.8
33.6
33.4
33.2
Temperature (°C)
14
13.5
13
12.5
12
11.5
Spiciness
0.8
0.6
0.4
0.2
0
−0.2
1998
1999
2001
2002
2003
2004

Fig. 10.



Salinity (psu)
0.1
0
−0.1
−0.2
−0.3
−0.4
Temperature (°C)
8
6
4
2
0
Potential density (σt, kg m−3)
0
−0.5
−1
−1.5
−2
Apr98
Apr99
May01
May02
Jun03
May04

Fig. 11.